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An Annual Report for

STUDIES OF DISKS AROUND THE SUN AND OTHER STARS
NAGW-4468

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INTRODUCTION

This is the January 1997 Annual report for NAGW-4468 (SwRI Project 15-7238), *Studies of Disks Around the Sun and Other Stars,* (S.A. Stern, PI; J.E. Colwell, CoI).

We are conducting research designed to enhance our understanding of the evolution and detectability of comet clouds and disks. This area holds promise for also improving our understanding of outer solar system formation, the bombardment history of the planets, the transport of volatiles and organics from the outer solar system to the inner planets, and to the ultimate fate of comet clouds around the Sun and other stars. According to "standard" theory, both the Kuiper Belt and the Oort Cloud are (at least in part) natural products of the planetary accumulation stage of solar system formation. One expects such assemblages to be a common attribute of other solar systems. Therefore, studies of such comet disks and clouds offer important insights into solar system architectural properties in extra-solar environments as well.

Our research program consists modeling collisions in the Kuiper Belt and extrapolating these results to the dust disks around other stars. The modeling effort focuses on moving from our simple, first-generation, Kuiper Belt collision rate model, to a time-dependent, second-generation model that incorporates physical collisions, velocity evolution, dynamical erosion, and various dust transport mechanisms. This second generation model is being used to study the evolution of surface mass density and the object-size spectrum in the Kuiper Belt.

This report summarizes the progress made to date in this research effort, which was funded beginning in January, 1995.

PROGRAM PROGRESS

1) In 1995 we reported the completion of the first model of collision rates in the Kuiper Belt. With this model we explored the rate of collisions among bodies in the present-day Kuiper Belt as a function of both the total mass and population size structure of the Belt. We found that collisional evolution is an important evolutionary process in the Belt as a whole, and indeed, that it is likely the dominant evolutionary process beyond ≈ 42 AU, where dynamical instability timescales exceed the age of the solar system. Two key findings we report from this modelling work are: (i) That unless the Belt's population structure is sharply truncated for radii smaller than $\sim$1–2 km, collisions between comets and smaller debris are occurring so frequently in the Belt, and with high enough velocities, that the small body (i.e., km-class object) population in the Belt has probably developed into a collisional cascade, thereby implying that the Kuiper Belt comets may not all be primordial, and (ii) that the rate of collisions of smaller bodies with larger $100 < R < 400$ km objects (like 1992QB$_1$ and its cohorts) is so low that there appears to be a dilemma in explaining how QB$_1$s could have grown by binary accretion in the belt as we know it. Given these findings, it appears that either the present-day belt is no longer representative of the ancient structure from which it evolved. In particular, it appears that the 30 50 AU region of the Kuiper Belt has very

likely experienced a strong decrease in its surface mass density over time. This in turn suggests the intriguing possibility that the present-day Kuiper Belt evolved through a more erosional stage reminiscent of the disks around the A-stars β Pictorus, α PsA, and α Lyr. These results were published in *The Astronomical Journal* in late-1995.

2) We have used this same model and a second code, IR signatures code to estimate the detectability of IR emission from debris created by collisions. We found that eccentricities in the Kuiper Belt are high enough to promote erosion on virtually all objects up to $\sim$ 30 km, independent of their impact strength. Larger objects, such as the 50–170 km radius "QB_1" population, will suffer net erosion if their orbital eccentricity is greater than ≈ 0.05 (≈ 0.1) if they are structurally weak (strong). The model predicts a net collisional erosion rate from all objects out to 50 AU ranging from 3×10^{16} to 10^{19} g yr,$^{-1}$ depending on the mass, population structure, and mechanical properties of the objects in the Belt. We find two kinds of collisional signatures that this debris should generate. First, there should be a relatively smooth, quasi-steady-state, longitudinally isotropic, far IR (i.e, ~ 60 μm peak) emission near the ecliptic in the solar system's invariable plane ecliptic, caused by debris created by the ensemble of ancient collisions. The predicted optical depth of this emission could be as low as 7×10^{-8}, but is most likely between 3×10^{-7} and 5×10^{-6}. We found that this signature was most likely below IRAS detection limits, but that it should be detectable by both ISO and SIRTF. Additionally, very recent impacts in the belt should produce short-lived, discrete clouds with significantly enhanced, localized IR emission signatures superimposed on the smooth, invariable plane emission. These discrete clouds should have angular diameters up to 0.2 deg, and annual parallaxes up to 2.6 deg. Individual expanding clouds (or trails) should show significant temporal evolution over timescales of a few years. As few as zero or as many as several 10^2 such clouds may be detectable in a complete ecliptic survey at ISO's sensitivity, depending on the population structure of the Kuiper Belt. This work was published in *Astronomy & Astrophysics* in mid-1996.

3) We then employed our static collision rate model model to study the collisional environment in the ancient Kuiper Belt. In particular, we explored the consequences of a massive, primordial Kuiper Belt using a collision rate model that assumes the dominant growth mechanism in the 35–50 AU region was pairwise accretion. We found that the growth of QB_1-class objects from seeds only kilometers in diameter required a very low eccentricity environment, with mean random eccentricities of order 1% or less. Duncan et al. (1995) have shown that the presence of Neptune induces characteristic eccentricities throughout the 30–50 AU region of a few percent or greater. We therefore concluded that growth of objects in the 30 to 50 AU zone to a least this size must have occurred before Neptune reached a fraction of its final mass. Once Neptune grew sufficiently to induce eccentricities exceeding $\approx$1%, we found that the belt environment became highly erosive for objects with radii smaller than $\sim$20–30 kilometers, which likely created a flattening in the belt's population power law slope between radius scales of $\approx$30 to $\approx$100 km, depending on the density and strength of such objects. This erosive environment could have resulted in sufficient

mass depletion to evolve the belt to its present, low-mass state, independent of dynamical losses (which surely also played an important role). During the period of rapid erosive mass loss, the belt probably exhibited optical depths of 10^{-4} to 10^{-5} (reminiscent of β Pictoris), for a timescale of $\sim 10^7$ to $\sim 10^8$ years. As a result of the evolution of the belt inside 50 AU, we suggested that (i) the present-day Solar System's surface mass density edge near 30 AU is actually only the inner edge of a surface mass density *trough*, and (ii) that the surface mass density of solids may rise back beyond ~50 AU, where the giant planets have never induced erosive high eccentricities. Indeed, the growth of objects in the region beyond 50 AU may be continuing to the present. This work was published in *The Astronomical Journal* in late 1996.

4) In late-1996 PI Stern and CoI Colwell were able to complete a key element of our research program: the development and certification testing of the new, *time-dependent* collisional evolution code, and to begin applying it to studies of the Kuiper Belt. This code took over 2 years to develop and validate. The first application we chose was to study the collisional erosion of the ancient Kuiper Belt into the far less massive, present-day structure. This issue also impinges directly on the origin of Pluto, the origin and nature of short-period comets, and (less directly) on the nature and origin of the dusty disks seen around many main sequence stars. Simple, static collision rate models have been used to predict that the Belt should evolve heavily under the influence of collisions that it loses between one and two orders of magnitude in mass over time. Here we investigate this topic in more detail by constructing the first time-dependent model of collisional evolution of the Belt between 30 and 70 AU. We find that under a wide range of assumptions, collisional evolution depletes the mass of the 30–50 AU zone by more than 95% over the age of the solar system, creating a surface mass density gap in this region, similar to what is observed. These findings demonstrate that a combination of collisional and dynamical evolution is needed to reduce the postulated, massive primordial Belt to roughly its current mass in the region inside ~ 50. These results also provide new evidence that the objects being detected in the present-day structure called the Kuiper Belt are more accurately residents of a *gap* in the heliocentric mass distribution of solids, which has been created by erosional collisions among the objects in the 30–50 AU zone. Our results support the prediction that the surface mass density of solids in the region beyond some 50 to ~70 AU increases dramatically, revealing a massive, more distant remnant of the primordial disk that surrounded the young Sun. These results were submitted by PI Stern and CoI Colwell as a Letter to *Nature*.

5) These research papers have been accompanied by two invited reviews. The first was submitted to the *Planetary Ices* book (expected to appear in 1997), summarizing the present state of knowledge about the Kuiper Belt and Pluto. The second review article was co-authored with H. Campins on the relationship of the Centaurs to the Kuiper Belt; it appeared in *Nature* in mid-1996. Additionally, in February 1997, an article by PI Stern appeared in the popular-level magazine *Astronomy* on extra-solar comets.

6) In the summer of 1995 we organized and sponsored a 2-day workshop on collisions in the Kuiper Disk. This workshop was attended by D. Davis (PSI), P. Farinella (Italy), R. Canup (U. Colorado), M. Festou (France), J. Colwell (U. Colorado), H. Levison (SwRI), and PI Stern (SwRI). The proceedings of this workshop were informally published and the distributed among the participants. A copy was also sent to Origins program scientist Trish Rogers.

7) In 1995, PI Stern gave 6 talks summarizing progress related to this research program. In 1996, PI Stern gave 5 additional talks summarizing the modelling results obtained under this Origins program. A list of the 1996 talks is attached to this report.

8) For 1997 we plan to exploit our new time-dependent collisional evolution code to better understand the growth of objects in the Kuiper Belt, and the implications of that growth for the formation of Neptune and Pluto.

RELEVANT PUBLICATIONS UNDER THIS GRANT

Collision Rates in the Kuiper Disk and Their Implications. S.A. Stern, *The Astronomical Journal*, **110**, 856, 1995.

Escapees from the Kuiper Disk: The Centaurs. Stern, S.A., and H. Campins, *Nature*, **382**, 507, 1996.

Signatures of Collisions in the Kuiper Disk. S.A. Stern. *Astronomy & Astrophysics*, **310**, 999, 1996.

The Collisional Environment, Timescales, and Architecture of the Ancient, Massive Kuiper Disk. Stern, S.A.. *The Astronomical Journal*, **112**, 1203, 1996.

Interstellar Intruders. S.A. Stern, *Astronomy Magazine*, February 1997.

Pluto and the Kuiper Disk. S.A. Stern. "Ices in the Solar System." (C. DeBergh, B. Schmitt, M.C. Festou, eds.), in press, 1997.

On the Origin of Pluto, Charon, and the Pluto-Charon Binary. S.A. Stern, W.B. McKinnon, and J.I. Lunine. Invited chapter for the UA Press Space Science Series volume, "Pluto & Charon," in press, 1997.

Collisional Erosion in the Edgeworth-Kuiper Belt. Stern, S.A., and J.E. Colwell. Submitted to Nature, 1996.

RELEVANT 1996 SCIENTIFIC PRESENTATIONS

1) The Origin of the Pluto-Charon System. Institute for Cosmic Research (IKI). Moscow, Russia. 21 May 1996. (Invited Lecture).

2) Collisions and the Architecture of the Kuiper Belt. Kuiper Belt Workshop. Institute for Theoretical Astrophysics. Toronto, Canada. 8 June 1996. (Invited Lecture).

3) Collisions in the Massive, Ancient Kuiper Disk. ACM V, Versailles, France. 10 July 1996. (Contributed Talk).

4) Collisions, Erosion, and Accretion in the Kuiper Disk. New Mexico State University, Department of Astronomy. Las Cruces, New Mexico. Departmental Seminar. 18 July 1996. (Invited Lecture).

5) Accretion in the Trans-Neptunian Region. Max Planck Institute for Radioastronomy Bonn, Germany. 10 Oct 1996. (Invited Lecture).

ATTACHMENT I